Chapter 3: Data Transmission

Terminology (1)

- Transmitter
- Receiver
- Medium
  - Guided medium
    - e.g. twisted pair, coaxial cable, optical fiber
  - Unguided medium
    - e.g. air, seawater, vacuum
Terminology (2)

• Direct link
  — No intermediate devices
• Point-to-point
  — Direct link
  — Only 2 devices share link
• Multi-point
  — More than two devices share the link

Terminology (3)

• Simplex
  — One direction
  — One side transmits, the other receives
    • e.g. Television
• Half duplex
  — Either direction, but only one way at a time
    • e.g. police radio
• Full duplex
  — Both stations may transmit simultaneously
  — Medium carries signals in both direction at same time
    • e.g. telephone
**Frequency, Spectrum and Bandwidth**

- Time domain concepts
  - Analog signal
    - Varies in a smooth way over time
  - Digital signal
    - Maintains a constant level then changes to another constant level
  - Periodic signal
    - Pattern repeated over time
  - Aperiodic signal
    - Pattern not repeated over time

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**Analogue & Digital Signals**

(a) Analog

(b) Digital
**Periodic Signals**

- **Sine Wave**
  - Peak Amplitude ($A$)
    - maximum strength of signal, in volts
  - Frequency ($f$)
    - Rate of change of signal, in Hertz (Hz) or cycles per second
    - Period ($T$): time for one repetition, $T = 1/f$
  - Phase ($\phi$)
    - Relative position in time
  - Periodic signal $s(t + T) = s(t)$
  - General wave $s(t) = A\sin(2\pi ft + \Phi)$
Periodic Signal: e.g. Sine Waves

\[ s(t) = A \sin(2\pi ft + \Phi) \]

- Period of the signal is \( \frac{2\pi}{f} \)
- Wavelength \( \lambda \) is the distance occupied by one cycle
- Distance between two points of corresponding phase in two consecutive cycles
- Wavelength formula:
  \[ \lambda = \frac{\text{distance}}{\text{number of cycles}} \]
- Assuming signal velocity \( v \):
  \[ \lambda f = v \]
  \[ c = 3 \times 10^8 \text{ m/s (speed of light in free space)} \]
Frequency Domain Concepts

• Signal is usually made up of many frequencies
• Components are sine waves
• It can be shown (Fourier analysis) that any signal is made up of component sine waves
• One can plot frequency domain functions

Building block for waves

• What is a square wave?
  — What frequency components are digital signals composed of?
  — How many components do I need to recreate a square wave?
  — What is a realistic spectrum?
  — Where is the main energy of the signal?
  — Below is a representation of a square wave with amplitude A:

\[
s(t) = \frac{A4}{\pi} \sum_{k_{\text{odd}}, k=1}^{\infty} \frac{1}{k} \sin(2\pi kft)
\]
Physical Aspects

• Limited Bandwidth
  — Fourier Analysis

\[ v(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos n\omega_0 t + \sum_{n=1}^{\infty} b_n \sin n\omega_0 t \]

\[ a_0 = \frac{1}{T} \int_0^T v(t) dt \]

\[ a_n = \frac{2}{T} \int_0^T v(t) \cos(n\omega_0 t) dt \]

\[ b_n = \frac{2}{T} \int_0^T v(t) \sin(n\omega_0 t) dt \]

\[ v(t) = \text{voltage as a function of time} \]

\[ \omega_0 = \text{fundamental frequency component in radians / second} \]

\[ f_s = \text{fundamental frequency in Hz} \]

\[ T = 1/f_s = \text{period in seconds} \]

Physical Aspects (cont.)

• Limited Bandwidth (cont.)
  — Unipolar

\[ v(t) = \frac{V}{2} + \frac{2V}{\pi} \left\{ \cos \omega_0 t - \frac{1}{3} \cos 3\omega_0 t + \frac{1}{5} \cos 5\omega_0 t - \ldots \right\} \]

— Bipolar

\[ v(t) = \frac{4V}{\pi} \left\{ \cos \omega_0 t - \frac{1}{3} \cos 3\omega_0 t + \frac{1}{5} \cos 5\omega_0 t - \ldots \right\} \]

How much bandwidth do we need?
What are the trade-offs if we compromise bandwidth?
Addition of Frequency Components ($T=1/f$)

Spectrum of previous example

Single pulse: between $-X/2$ and $X/2$
Spectrum & Bandwidth

- Spectrum
  - range of frequencies contained in signal
- Absolute bandwidth
  - width of spectrum
- Effective bandwidth
  - Often just bandwidth
  - Narrow band of frequencies containing most of the energy
- DC Component
  - Component of zero frequency

Signal with DC Component
Data Rate and Bandwidth

- Any transmission system has a limited band of frequencies
- This limits the data rate that can be carried
- Issues
  - The more bandwidth the less distortion
  - Where is the bulk of the energy?

Analog and Digital Data Transmission

- Data
  - Entities that convey meaning
- Signals
  - Electric or electromagnetic representations of data
- Transmission
  - Communication of data by propagation and processing of signals
Analog and Digital Data

- Analog
  - Continuous values within some interval
  - e.g. sound, video
- Digital
  - Discrete values
  - e.g. text, integers

Acoustic Spectrum (Analog)
Analog and Digital Signals

- Means by which data are propagated
- Analog
  - Continuously variable
  - Various media
    - Wire, fiber optic, space
  - Speech bandwidth 100Hz to 7kHz
  - Telephone bandwidth 300Hz to 3400Hz
  - Video bandwidth 4MHz
- Digital
  - Use two DC components

Advantages & Disadvantages of Digital

- Cheaper
- Less susceptible to noise
- Greater attenuation
  - Pulses become rounded and smaller
  - Leads to loss of information
**Components of Speech**

- Frequency range (of hearing) 20Hz-20kHz
  - This upper bound is over-optimistic though!
  - Speech 100Hz-7kHz
- Easily converted into electromagnetic signal for transmission
- Sound frequencies with varying volume converted into electromagnetic frequencies with varying voltage
- Limit frequency range for voice channel
  - 300-3400Hz

**Attenuation of Digital Signals**

Voltage at transmitting end

Voltage at receiving end
Video Components

- USA - 483 lines scanned per frame at 30 frames per second
  - 525 lines but 42 lost during vertical retrace
- So 525 lines x 30 scans = 15750 lines per second
  - 63.5 $\mu$s per line, (11 $\mu$s for retrace, so 52.5 $\mu$s per video line)
- Max frequency if line alternates black and white
- Horizontal resolution is about 450 lines giving 225 cycles of wave in 52.5 $\mu$s
- Max frequency of 4.2MHz

Binary Digital Data

- From computer terminals etc.
- Two dc components
- Bandwidth depends on data rate
Conversion of PC Input to Digital Signal

- as generated by computers etc.
- has two dc components
- bandwidth depends on data rate

![Graph demonstrating the conversion of PC input to digital signal.](image)

User input at a PC is converted into a stream of binary digits (1s and 0s). In this graph of a typical digital signal, binary one is represented by +5 volts and binary zero is represented by -5 volts. The signal for each bit has a duration of 0.02 msec, giving a data rate of 50,000 bits per second (50 kbps).

Data and Signals

- Usually use digital signals for digital data and analog signals for analog data
- Can use analog signal to carry digital data
  - Modem
- Can use digital signal to carry analog data
  - Compact Disc audio
Analog Signals Carrying Analog and Digital Data

Analog Signals: Represent data with continuously varying electromagnetic wave

Analog Data (voice sound waves) → Analog Signal → Telephone

Digital Data (binary voltage pulses) → Analog Signal (modulated on carrier frequency) → Modem

Digital Signals Carrying Analog and Digital Data

Digital Signals: Represent data with sequence of voltage pulses

Analog Signal → Digital Signal → Codec

Digital Data → Digital Signal → Digital Transceiver
Transmission Impairments

- Signal received may differ from signal transmitted causing:
  - analog - degradation of signal quality
  - digital - bit errors
- Most significant impairments are
  - attenuation and attenuation distortion
  - delay distortion
  - noise

Attenuation

- Signal strength falls off with distance
- Depends on medium
- Received signal strength:
  - must be enough to be detected
  - must be sufficiently higher than noise to be received without error
- Attenuation is an increasing function of frequency
Noise (1)

- Additional signals inserted between transmitter and receiver
- Thermal
  - Due to thermal agitation of electrons
  - Uniformly distributed
  - White noise
- Intermodulation
  - Signals that are the sum and difference of original frequencies sharing a medium
Noise (2)

- Crosstalk
  - A signal from one line is picked up by another
- Impulse
  - Irregular pulses or spikes
  - e.g. External electromagnetic interference
  - Short duration
  - High amplitude

Digital Transmission

- Concerned with content
- Integrity endangered by noise, attenuation etc.
- Repeaters
  - Repeater receives signal
  - Extracts bit pattern
  - Retransmits
  - Attenuation is overcome
  - Noise is not amplified
Analog Transmission

- Analog signal transmitted without regard to content
- May be analog or digital data
- Attenuated over distance
- Use amplifiers to boost signal
- Also amplifies noise

Advantages of Digital Transmission

- Digital technology
  - Low cost LSI/VLSI technology
- Data integrity
  - Longer distances over lower quality lines
- Capacity utilization
  - High bandwidth links economical
  - High degree of multiplexing easier with digital techniques
- Security & Privacy
  - Encryption
- Integration
  - Can treat analog and digital data similarly
Delay Distortion

—Different frequency components of a signal
  • are attenuated differently, and
  • travel at different speeds through guided media

—This may lead to **delay distortion**

Channel Capacity

• Data rate
  —In bits per second, bps (not Bps)
  —Rate at which data can be communicated

• Bandwidth
  —In cycles per second, Hertz, Hz
  —Constrained by transmitter and medium

• Convention: not all “k”s are equal
  —data rates are given as power of 10
    • e.g., kHz is 1000Hz
  —data is given in terms of power of 2
    • e.g., KByte is 1024 Bytes
Nyquist Bandwidth

• If rate of signal transmission is 2B then a signal with frequencies no greater than B is sufficient to carry the signal rate.
  — Why? Assume we have a square wave of repeating 101010. If a positive pulse is a 1 and a negative pulse is 0, then each pulse lasts 1/2 \( T_1 \) \( (T_1 = 1/f_1) \) and the data rate is 2\( f_1 \) bits per second.

Nyquist Bandwidth

• If we limit the components to a maximum frequency (restrict the bandwidth) we need to make sure the signal is accurately represented.
• Based on the accuracy we require, the bandwidth can carry a particular data rate. The theoretical maximum communication limit is given by the **Nyquist** formula:

\[
C = 2B \log_2 M
\]

\( C \) = capacity or data transfer rate in bps
\( B \) = bandwidth (in hertz)
\( M \) = number of possible signaling levels
Signal Strength

— An important parameter in communication is the strength of the signal transmitted. Even more important is the strength being received.

— As signal propagates it will be attenuated (decreased)

— Amplifiers are inserted to increase signal strength

— Gains, losses and relative levels of signals are expressed in decibels
  - This is a logarithmic scale, but strength usually falls logarithmically
  - Calculation of gains and losses involves simple addition and subtraction

— Decibel measure of difference in two power levels is

\[
N_{dB} = 10 \log_{10} \frac{P_1}{P_2}
\]

Physical Aspects

— Signal Attenuation and Distortion
  - As a signal propagates across a transmission medium its amplitude decreases. This is known as signal attenuation.

  — A typical signal consists of a composition of many frequency components (Fourier Analysis). Due to the limited transmission bandwidth of a medium, the higher frequency components may not be able to be transmitted.
    - Recall the Nyquist formula

\[
C = 2B \log_2 M \quad \quad \log_2(x) = \frac{\ln (x)}{\ln (2)}
\]
Shannon capacity

—A transmission line may experience interference from a number of sources, called noise. Noise is measured in terms of signal to noise power ratio, expressed in decibels:

\[
\left( \frac{S}{N} \right)_\text{dB} = 10 \log_{10} \left( \frac{S}{N} \right)
\]

—The effects of noise on channel capacity can be seen using the Shannon-Hartley Law:

\[
C = B \log_2 \left( 1 + \frac{S}{N} \right) \text{bps}
\]

\[C = \text{data transfer rate in bps}\]
\[B = \text{bandwidth (in Hertz)}\]

Cross Talk -- NEXT canceling

—near-end crosstalk (NEXT), cross talk of strong transmit (output) signal to weak receive (input) signal.

—adaptive NEXT canceling using op-amp
Noise

• Impulse Noise
  —impulse caused by switching, lightning etc.

• Thermal Noise
  —present irrespective of any external effects
  —caused by thermal agitation of electrons

Noise

• White Noise
  —random noise – entire spectrum

• Pink Noise
  —“realistic spectrum”
  —the power spectral density is inversely proportional to the frequency
**Combined Effects**

- Attenuation
- Limited Bandwidth
- Noise

It all adds up!

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**Thermal Noise**

— Energy (in joules = watts x seconds) per bit in a signal:

\[ E_b = ST_b \]

\( S = \text{signal power in watts} \)

\( T_b = \text{time period for 1 bit in seconds} \)

— Data Transmission rate \( R = 1/T_b \)

— Thermal noise \( N_0 \) in a line is: (\( T \) is temperature in K)

\[ N_0 = kTW \text{ where } k = 1.3803 \times 10^{-23}\text{ joule K}^{-1} \]

\( k \) is Boltzmann constant

\[ W \] is the bandwidth

\[ \frac{E_b}{N_0} = \frac{S/R}{N_0} = \frac{S/R}{kTW} \]
**Signal Delay**

— There exists a **transmission propagation delay** in any medium
  - Speed of light $3 \times 10^8 \text{ ms}^{-1}$
  - Speed of EM in cable/wire $2 \times 10^8 \text{ ms}^{-1}$

— Important parameter is **round-trip-delay**
  (time from first bit sent to last bit acknowledged)

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**Signal Delay**

— Propagation delay $T_p$ and transmission delay $T_x$

$$ T_p = \frac{d}{V}, \quad T_x = \frac{n}{R} $$

— Important ratio

$$ \frac{T_p}{T_x} $$

$d$ = distance in meters  
$V$ = EM speed  
$n$ = number of bits transmitted  
$R$ = link bit rate in bits per second